Asymmetries and Tau Polarization at LEP

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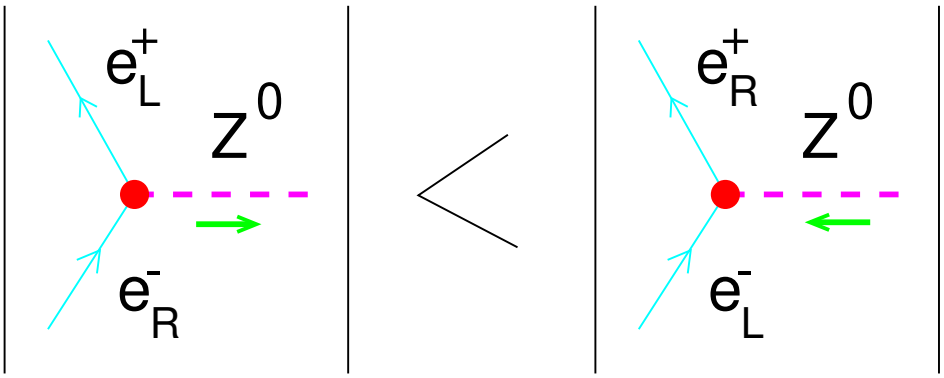
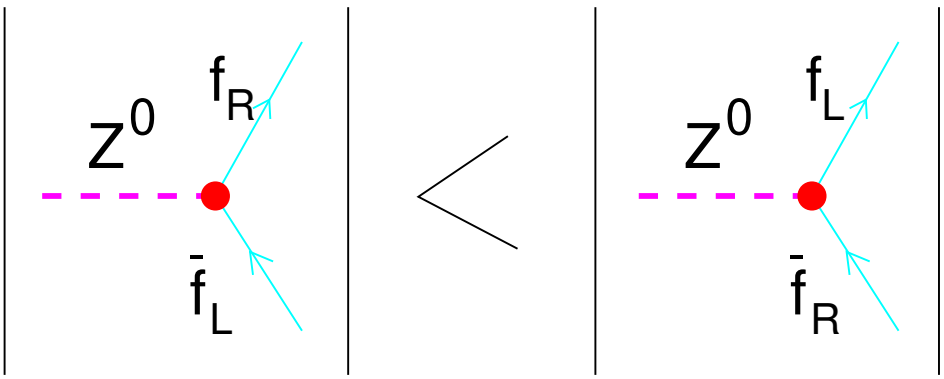
Introduction

Asymmetry at LEP caused by small parity violation in leptonic Z^0 couplings:



$\rightarrow$ Z^0 polarized: $\mathcal{A}_e = \frac{2\,\hat{g}_v^e\,\hat{g}_a^e}{(\hat{g}_v^e)^2+(\hat{g}_a^e)^2}$.

Similar in decay:



$\rightarrow$ final state polarized $\mathcal{A}_f = \frac{2\,\hat{g}_v^f\,\hat{g}_a^f}{(\hat{g}_v^f)^2+(\hat{g}_a^f)^2}$.

Observables

- Residual polarization of final state (measurable in τ decays)

$$\langle P_\tau \rangle = \frac{\sigma_r - \sigma_l}{\sigma_r + \sigma_l} \approx -\mathcal{A}_\tau$$

- Polarization asymmetry

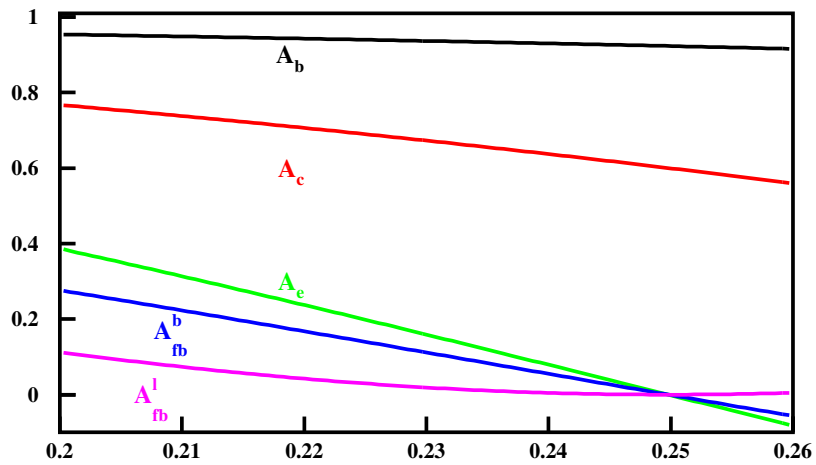
$$A_{\rm FB}^{\rm pol} = \frac{(\sigma_r^F - \sigma_l^F) - (\sigma_r^B - \sigma_l^B)}{\sigma_{tot}} \approx -\frac{3}{4}\mathcal{A}_e$$

- Forward-backward charge asymmetry

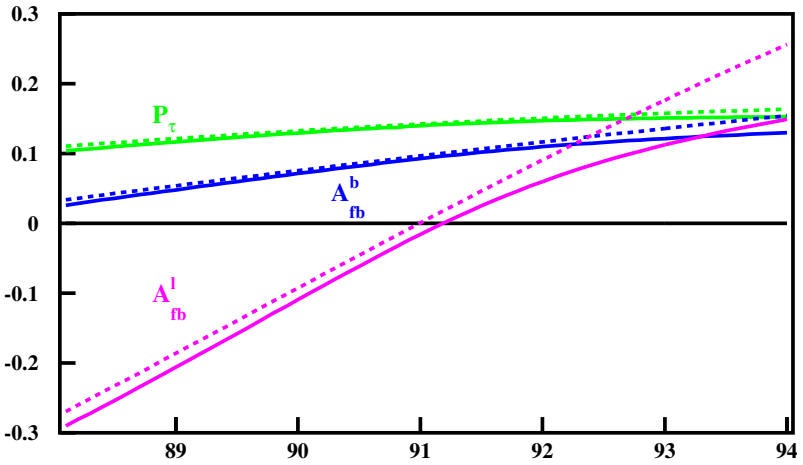
$$A_{\rm FB}^f = \frac{\sigma_f^F - \sigma_f^B}{\sigma_f^F + \sigma_f^B} = \frac{3}{4}\mathcal{A}_e \cdot \mathcal{A}_f$$

Observables related to $\sin^2\theta^{\,l}_{\rm eff}$:

$$\mathcal{A}_f = \frac{2(1-4|Q_f|\sin^2\theta^{\,l}_{\rm eff})}{1+(1-4|Q_f|\sin^2\theta^{\,l}_{\rm eff})^2}$$



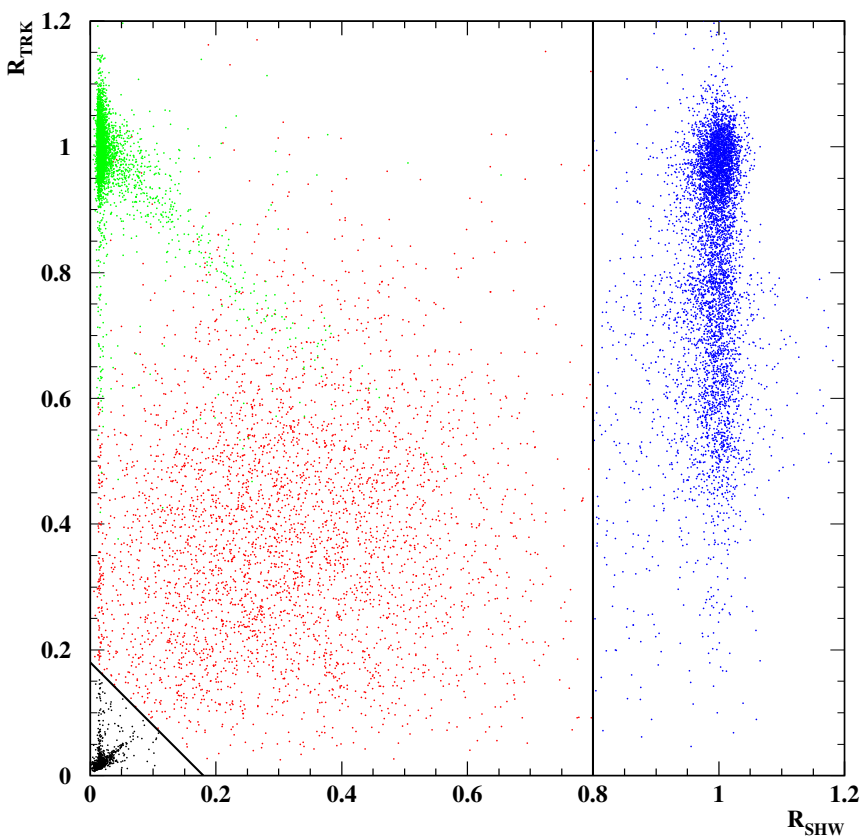
ISR, γ, γZ and $\sqrt{s}$ modify pure Z^0 effects:



Lepton charge asymmetries

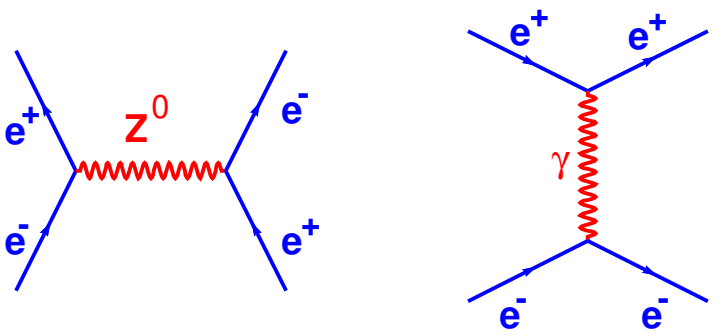
Conceptually 'cleanest' measurement at LEP (in particular $\mu^+\mu^-$)

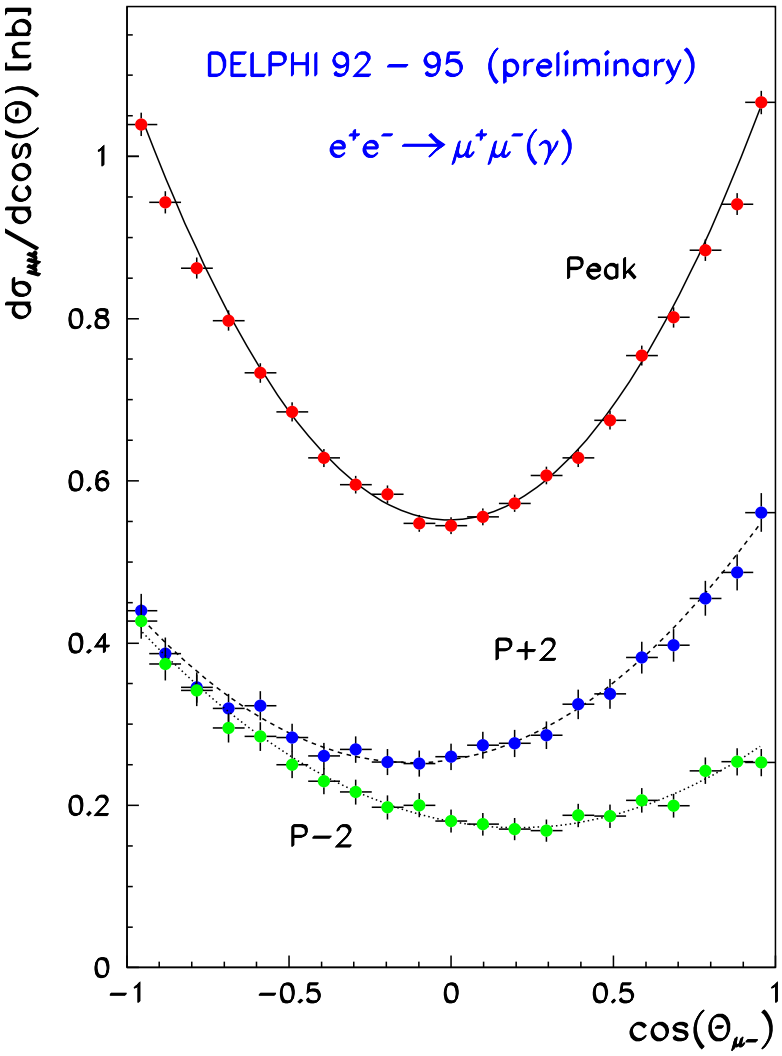
- clear separation of lepton species



- unambiguous charge identification

- A_{FB}^{ℓ} is ratio of numbers
  $\rightarrow$ luminosity uncertainty and most slection systematics cancel
- t-channel diagrams complicate e^+e^- channel





A_{FB} determined in maximum likelihood fit to differential distribution

$$\frac{1}{\sigma} = \frac{d\sigma}{d\cos\theta} = \frac{3}{8}\left(1+\cos^2\theta\right) + A_{\mathrm{FB}}\cos\theta$$

Systematics

Systematics of A_{FB} measurement

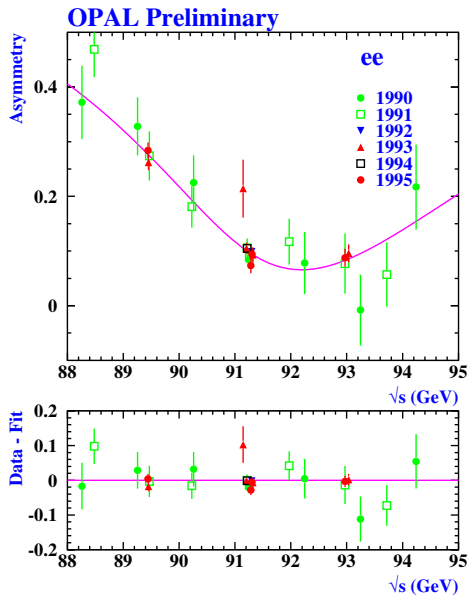
- charge & efficiency symmetry of detector & selection
- fiducial cut on angular range (e^+e^- t-channel)
- background (e^+e^- for $\tau^+\tau^-$)
- physics (asymmetric acceptance for e^+e^-, τ polarization)

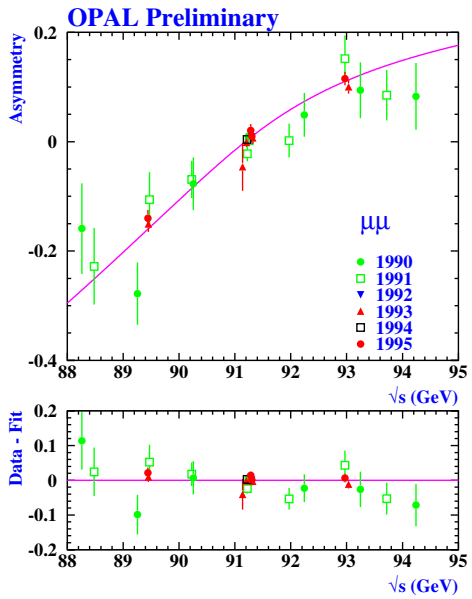
in general small, well below statistics.

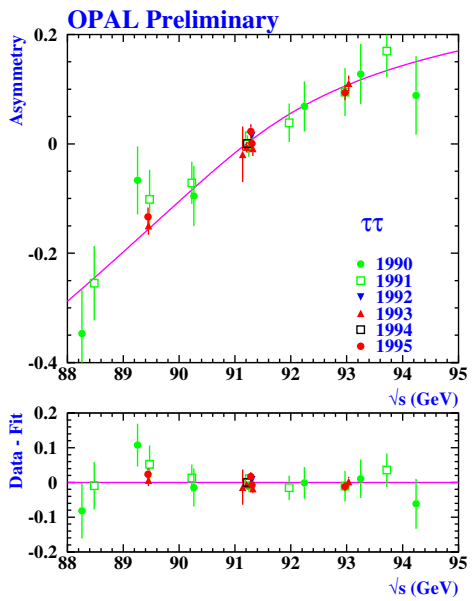
$A_{\mathrm{FB}}^{0,\ell}$ determined in global lineshape fit to σ and asymmetries, accounts for all effects of ISR, γ, γZ and $\sqrt{s}$.

t-channel correction done with ALIBABA/TOPAZ.
Introduces additional systematics of ≈ 0.0013 and correlations with $\sigma_{e^+e^-}$.
$\rightarrow$ Common to all experiments

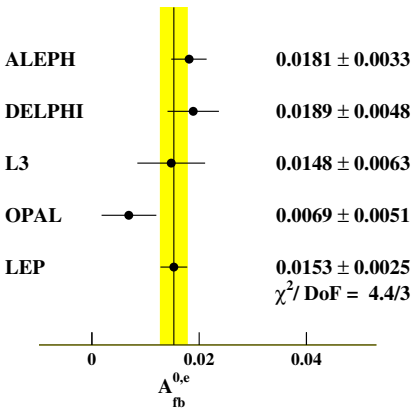
Results

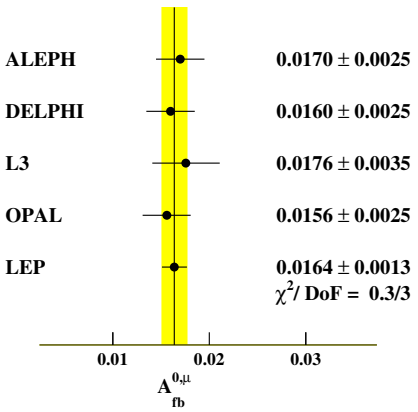

OPAL Preliminary
ee
1990
1991
1992
1993
1994
1995
Asymmetry
Data - Fit
√s (GeV)

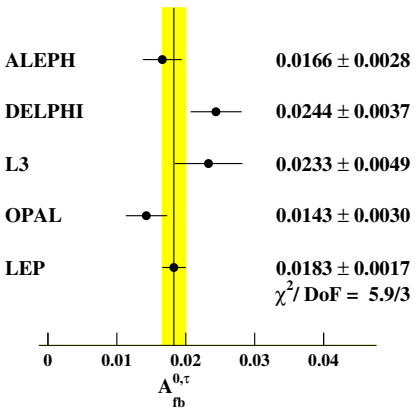

OPAL Preliminary
μμ
1990
1991
1992
1993
1994
1995
Asymmetry
Data - Fit
√s (GeV)

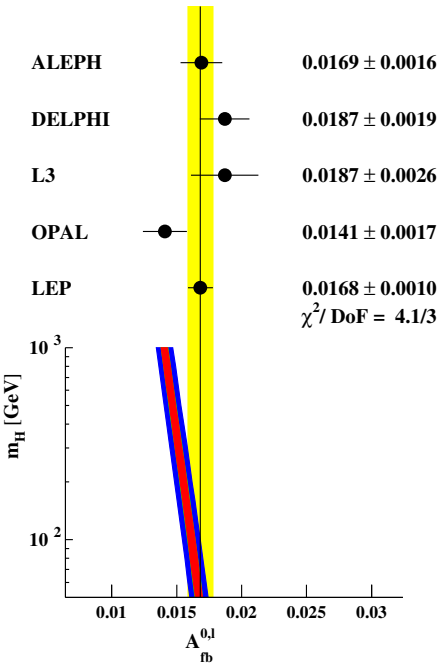

OPAL Preliminary
ττ
1990
1991
1992
1993
1994
1995
Asymmetry
Data - Fit
√s (GeV)

Results

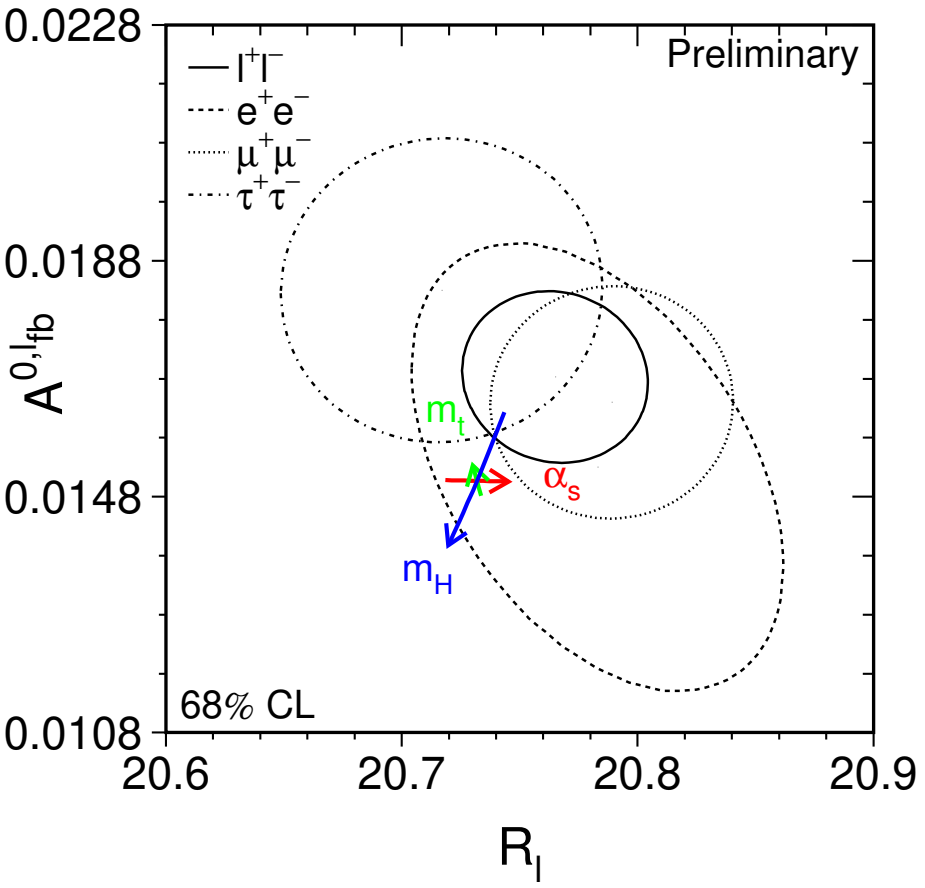

ALEPH
DELPHI
L3
OPAL
LEP
0.0181 ± 0.0033
0.0189 ± 0.0048
0.0148 ± 0.0063
0.0069 ± 0.0051
0.0153 ± 0.0025
χ²/ DoF = 4.4/3
0
0.02
0.04
A^{0,e}_{fb}


ALEPH
DELPHI
L3
OPAL
LEP
0.0170 ± 0.0025
0.0160 ± 0.0025
0.0176 ± 0.0035
0.0156 ± 0.0025
0.0164 ± 0.0013
χ²/ DoF = 0.3/3
0.01
0.02
0.03
A^{0,μ}_{fb}


ALEPH
DELPHI
L3
OPAL
LEP
0.0166 ± 0.0028
0.0244 ± 0.0037
0.0233 ± 0.0049
0.0143 ± 0.0030
0.0183 ± 0.0017
χ²/ DoF = 5.9/3
0
0.01
0.02
0.03
0.04
A^{0,τ}_{fb}


ALEPH
DELPHI
L3
OPAL
LEP
0.0169 ± 0.0016
0.0187 ± 0.0019
0.0187 ± 0.0026
0.0141 ± 0.0017
0.0168 ± 0.0010
χ²/ DoF = 4.1/3
10³
10²
m_H [GeV]
0.01
0.015
0.02
0.025
0.03
A^{0,l}_{fb}

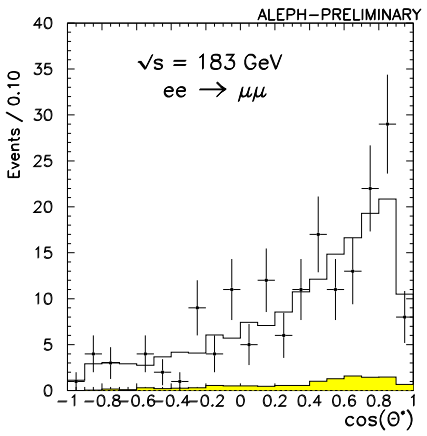
Lepton cross sections and asymmetries

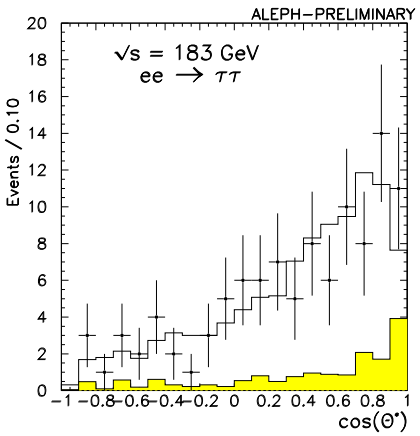


Asymmetry at LEP2

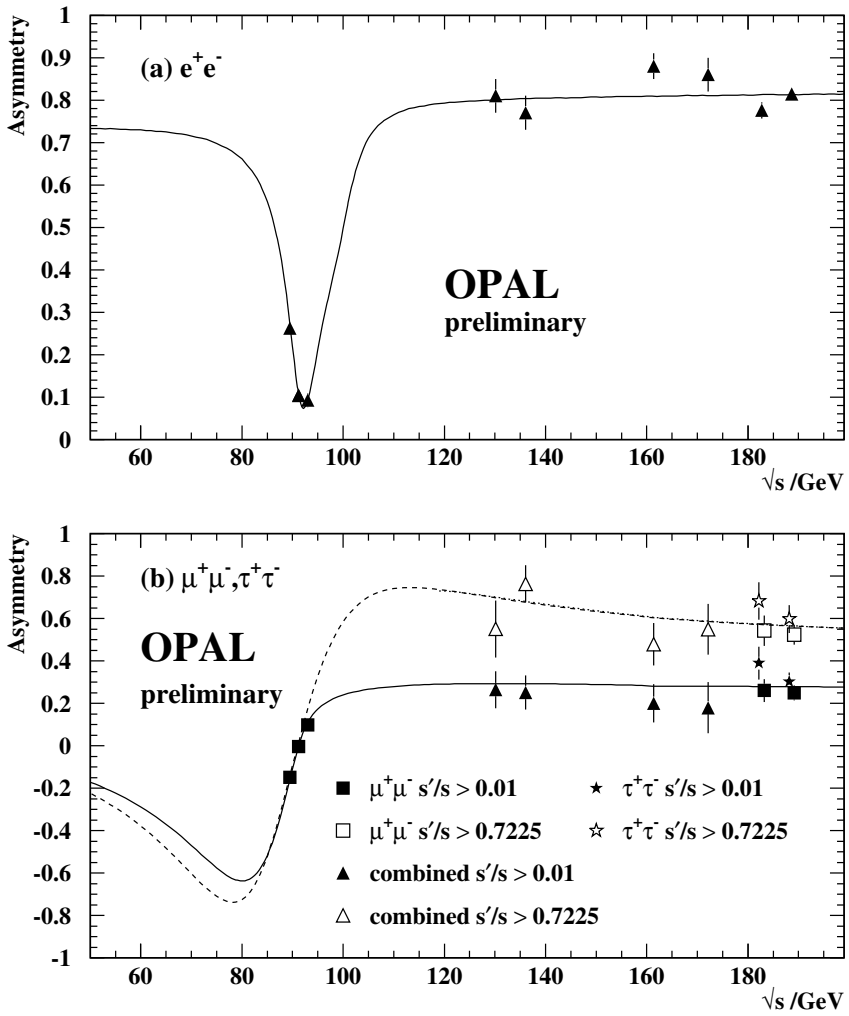
Measurements continue at LEP2

- γ exchange dominates, $\sigma_{\ell\ell}$ reduced by factor ≈ 500, correspondingly less statistics.
- large fraction of 'radiative return' events
- analysis separated for inclusive ($\sqrt{s'/s} > 0.10$) and non-radiative ($\sqrt{s'/s} > 0.85$)





Asymmetry at LEP2



Results consistent with Standard Model expectations

Quark asymmetries

Hadronization obscures both flavour and charge of the primary quark.

Precise measurements possible for b and c

Two principal methods:

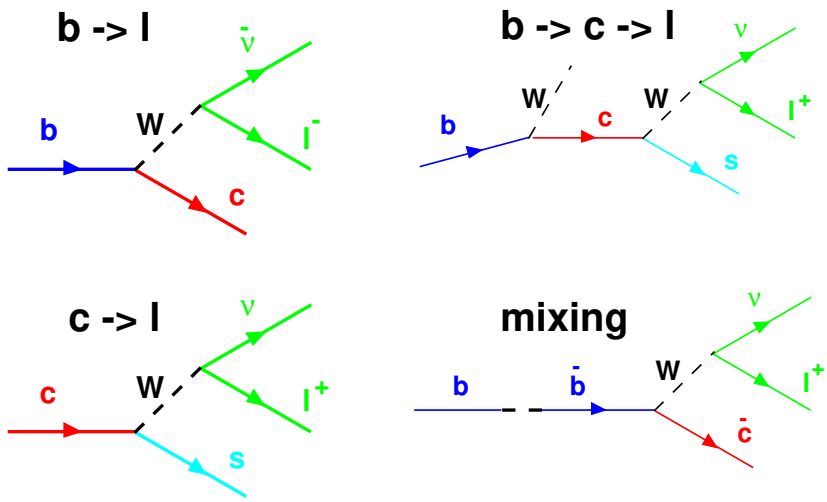
- particle tag (leptons, D-mesons) gives both quark flavour and charge.
- lifetime tag selects flavour,
  jet or hemisphere charge determines
  (statistically) primary quark charge.

$$Q_{jet} \equiv \frac{\sum_i Q_i |p_i^{||}|^\kappa}{\sum_i |p_i^{||}|^\kappa}$$

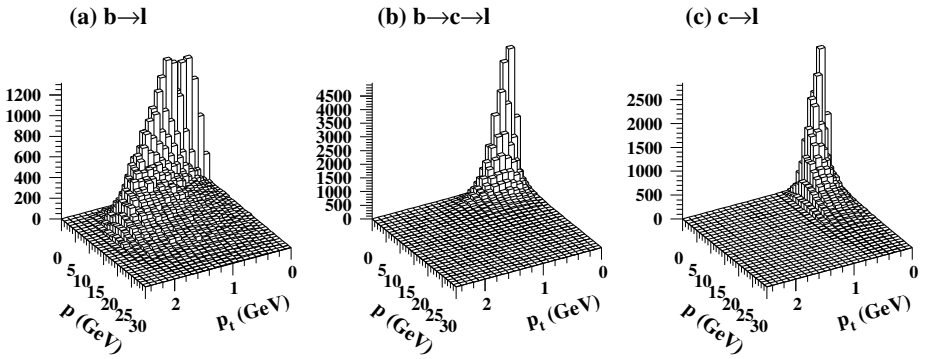
Lepton tags

Classical method to determine charge & and flavour of heavy quarks.

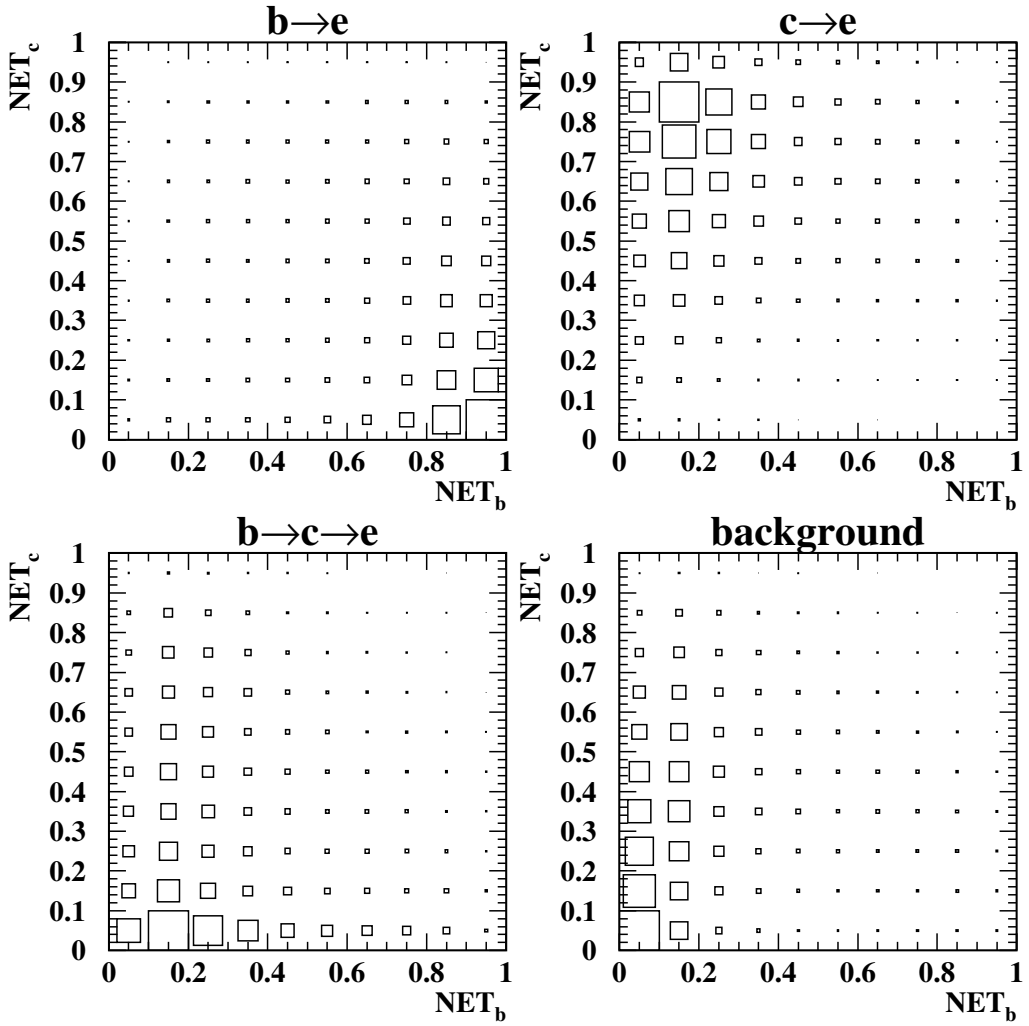
- Several sources must be distinguished



- Separation based on (p, p_T) of lepton w.r.t. jet axis



- Further improvement using additional info (lifetime, jet-shape) and neural net



- Uncertainties from
  - lepton spectra
  - leptonic branching ratios
  - mixing

  Best to determine $A^b_{\rm FB}$ and $A^c_{\rm FB}$ (+ mixing) in common fit.

	ALEPH	DELPHI	L3	OPAL
$A^b_{\rm FB}$	X	X	X	X
$A^c_{\rm FB}$		X		X
$\overline{\chi}$	X			X

$D^{(*)}$ reconstruction

$D^{(*)}$ mesons originate from two sources:

1. primary c quark + fragmentation quark
2. Deacy product of primary B meson

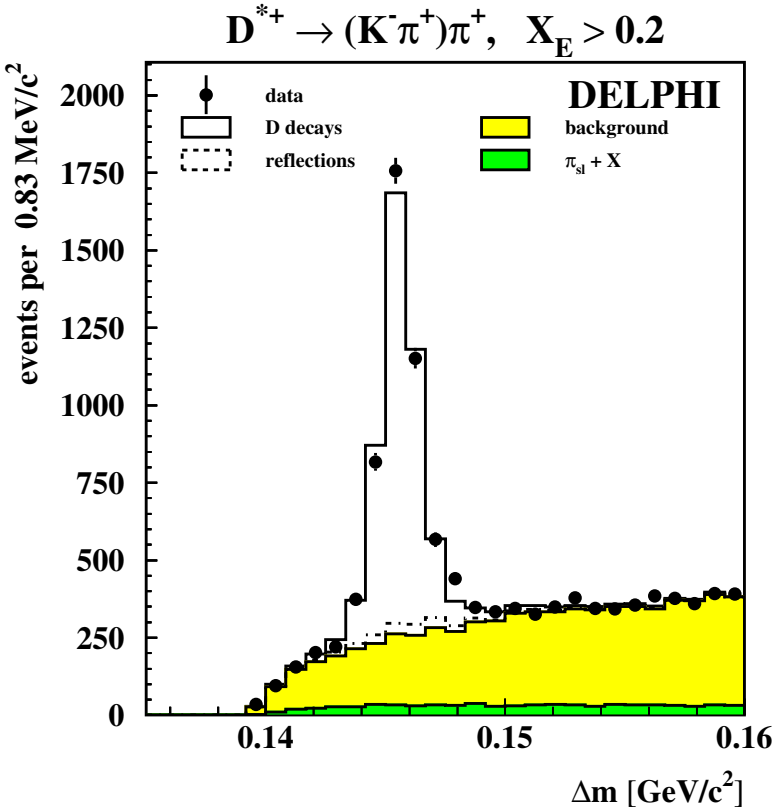
$\rightarrow$ both heavy flavour tag and charge id

D mesons reconstructed in various channels:

$$D^0 \rightarrow K^- \pi^+ \, , \; D^+ \rightarrow K^- \pi^+ \pi^+$$

$$\begin{aligned} D^{*+} \quad \rightarrow \quad & D^0 \pi^+ \\ & \mid\!\rightarrow K^- \pi^+ \\ & \mid\!\rightarrow K^- \pi^+ \pi^0 \\ & \mid\!\rightarrow K^- \pi^+ \pi^- \pi^+ \\ & \mid\!\rightarrow \ldots \end{aligned}$$

Slow pion characteristic signature for D^*:



D reconstruction used for $A_{\rm FB}^c$ by A D O.
Background from $B \to D$ decays controlled with D-momentum, lifetime, jet-shapes.

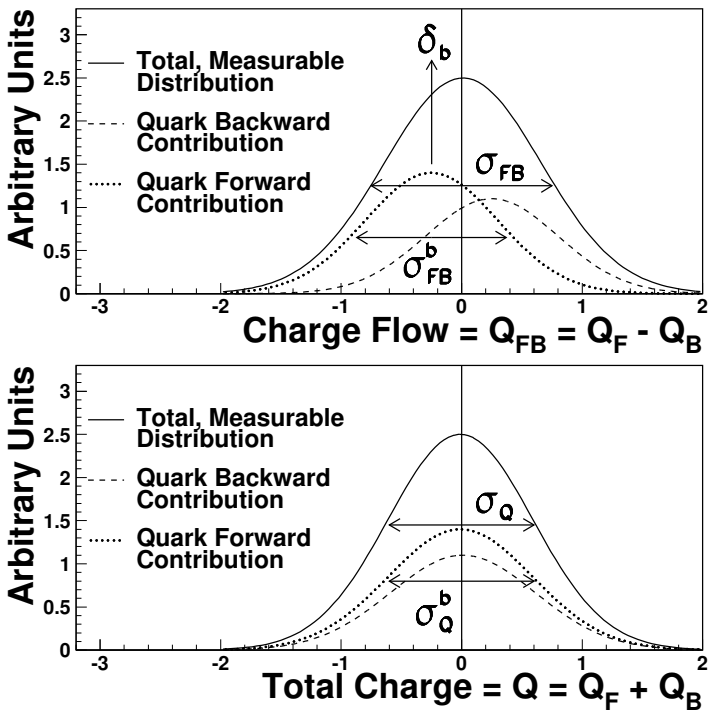
Jet charge

- Efficient & pure lifetime tags to select $b\bar{b}$ events.
- charge asymmetry

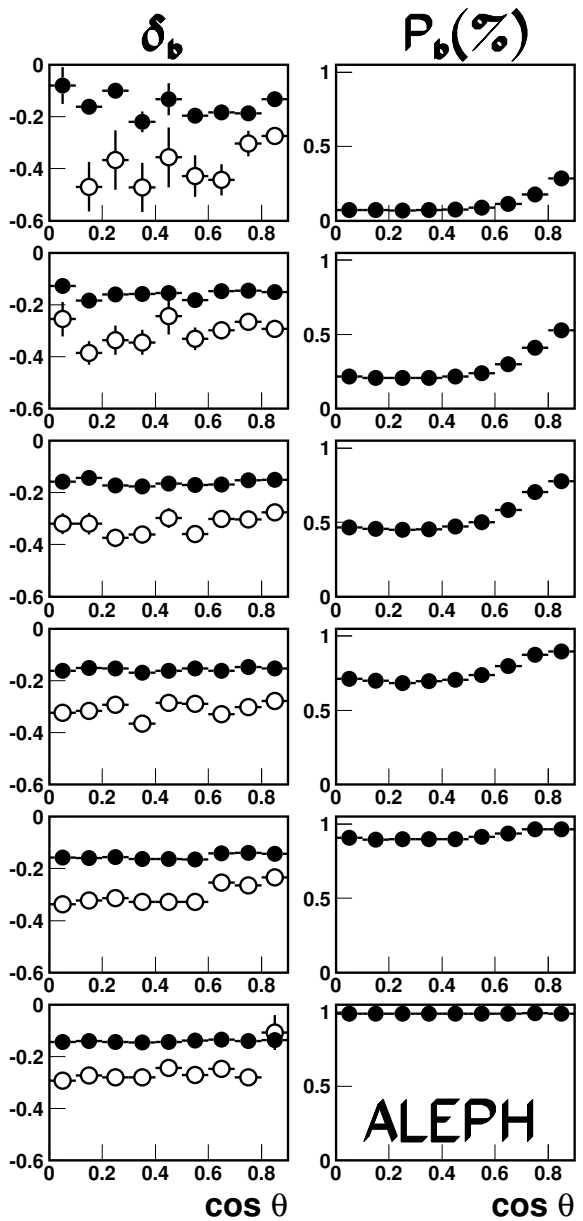
$$\langle Q_F - Q_B \rangle = \frac{N_F - N_B}{N_F + N_B} \langle Q_b - Q_{\bar{b}} \rangle = A_{\mathrm{FB}} \cdot \delta$$

- For a single flavour δ measured with data:

$$\delta \approx -4 \langle Q_F Q_B \rangle$$



- Correction to δ due to charge bias, background and correlations.
- Analogy to R_b double tag: Observable and main correction determined with data.
- Effects of QCD & $B^0\overline{B^0}$ mixing $\approx$ absorbed in δ
- Sophisticated techniques to extract maximal information:
  Fit as function of
  - b-purity
  - $\cos\theta$
  - κ ($Q_{jet} = \sum_i Q_i |p_i^{||}|^\kappa \,/\, \sum_i |p_i^{||}|^\kappa$)



A_{FB}^{b}

0.0625 ± 0.0192

0.1091 ± 0.0126

0.1021 ± 0.0094

0.0935 ± 0.0078

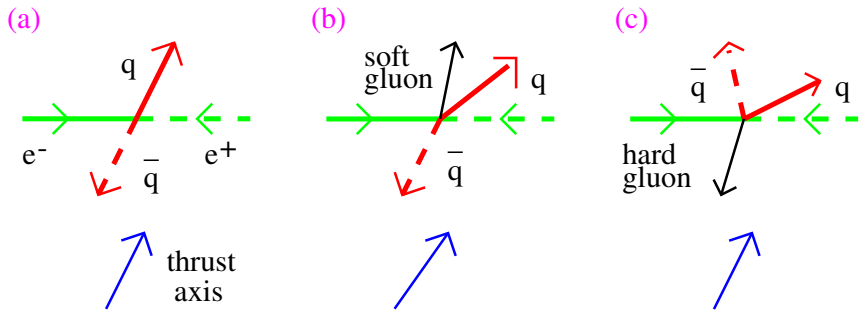
0.1041 ± 0.0063

0.1115 ± 0.0068

A^q_{FB} corrections

Measured A^q_{FB} $\rightarrow$ pure Z^0 $A^{0,q}_{\mathrm{FB}}$

- 'oblique' corrections due to ISR, γ, γZ and $\sqrt{s}$.
- Large QCD corrections ($\approx$ error), depending on details of analysis



$$A^q_{\mathrm{FB}} = (1 - B_{exp}\delta_{QCD})A^{0,q}_{\mathrm{FB}}$$

- δ_{QCD} analytically calculable ($\approx 5\,\%$)
- B_{exp} additional experimental bias, specific for experiment and method:

  leptons 0.5

  D recon. 0.2

  jet-charge < 0.1

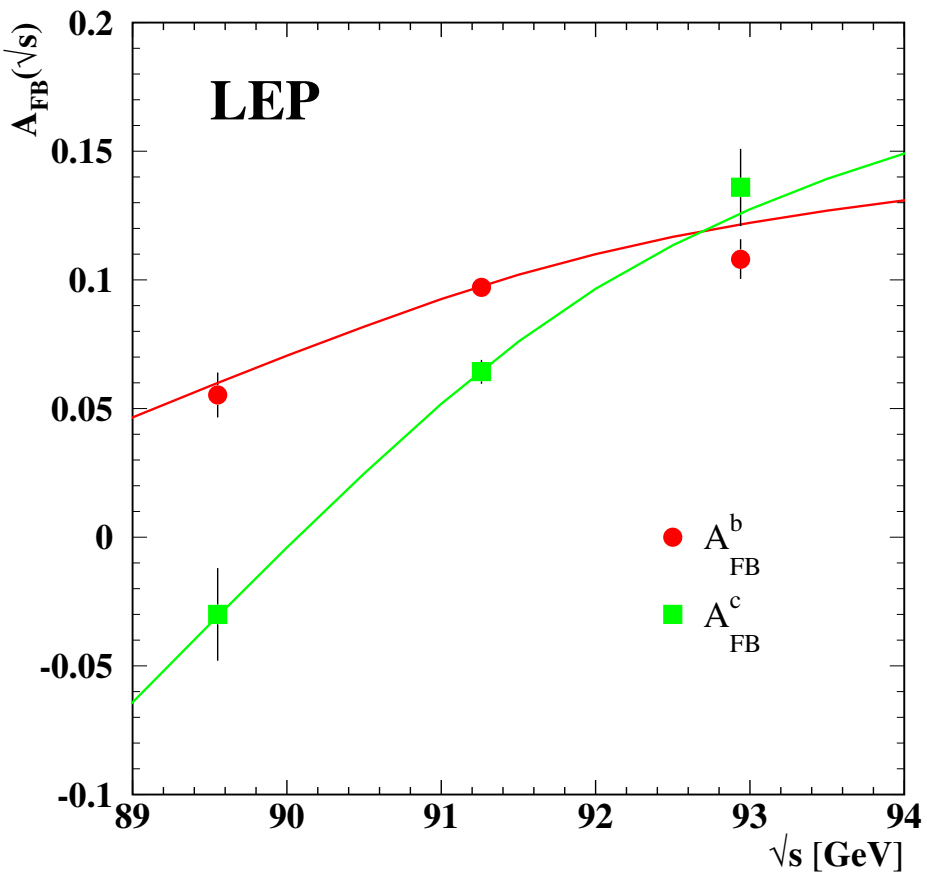
Combination of heavy flavour results

Averaging heavy flavour results from different analyses & experiments complicated due to

- Correlations between e-weak observables (R_b, R_c)
- Correlations between physics input (mixing, production and decay rates)

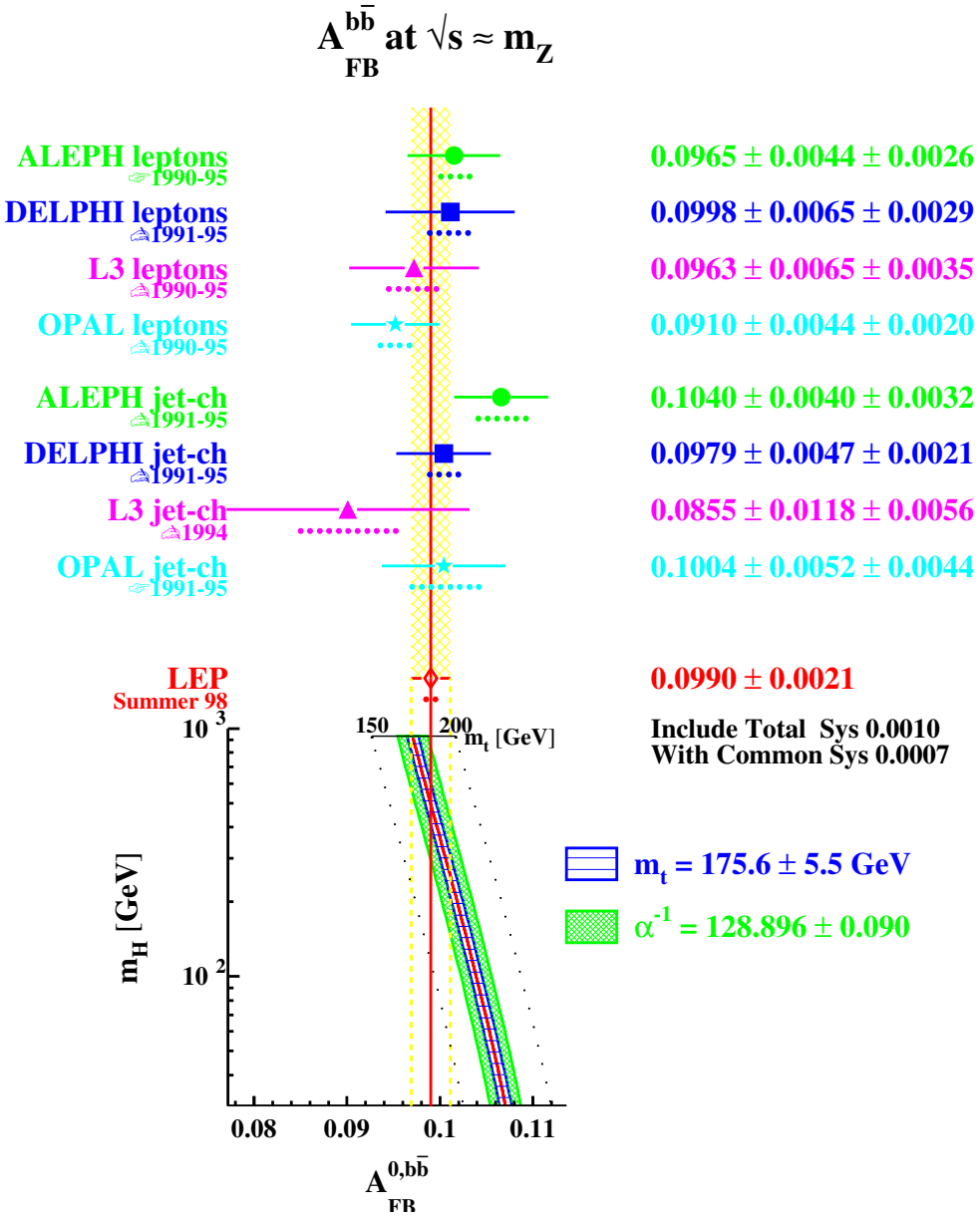
LEP & SLD agreed on common definition of input parameters & errors.
Averaging done by fit to 88 input quantities from LEP & SLD
$\rightarrow$ 17 fit parameters.

$A_{\mathrm{FB}}^{b,c}$ energy dependence

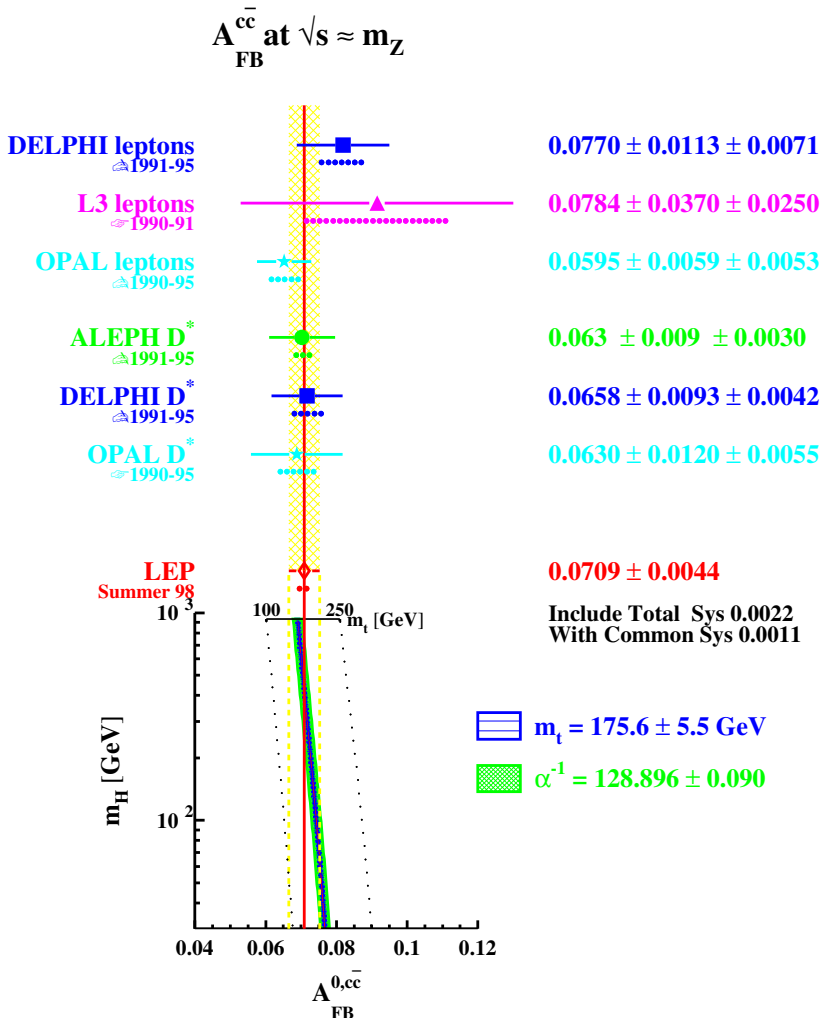


Off-peak measurements consistent with SM expectation.

$A_{\mathrm{FB}}^{0,b}$ results



$A_{\mathrm{FB}}^{0,c}$ results

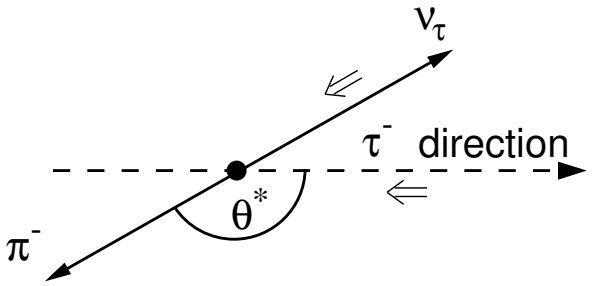


Tau polarization

τ only fermion where polarization precisely measureable.

- $(V-A)$ structure of τ charged current decay causes maximal parity violation.
- Decay directions in τ rest frame depend on polarization.

Most evident for $\tau \to \pi\nu$



$$\frac{dN}{d\cos\theta^*} \propto (1 + P_\tau \cos\theta^*)$$

$\cos\theta^*$ in τ rest frame related to E/E_{beam} in lab frame

$$\cos\theta^* \approx 2\frac{E_\pi}{E_{beam}} - 1$$

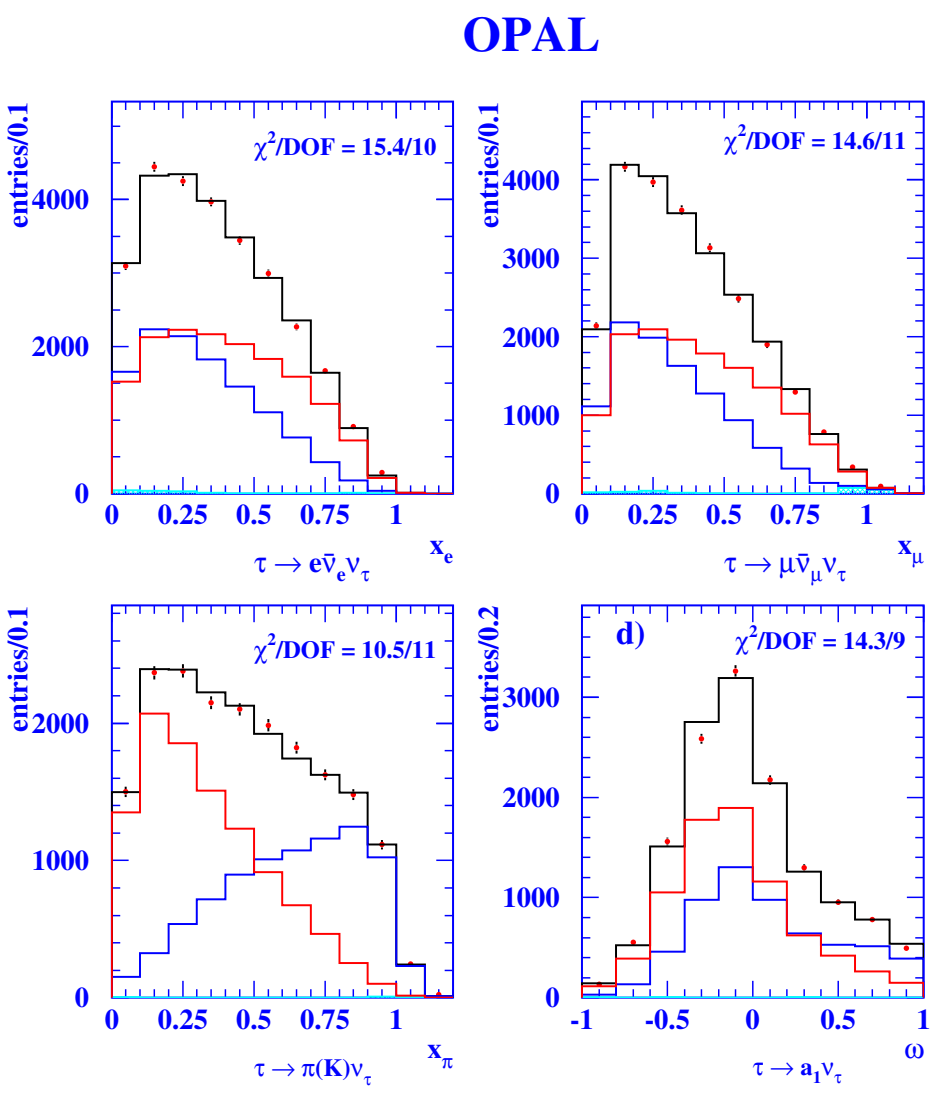
Other channels less direct:

- $\tau^- \to e^- \overline{\nu}_e \nu_\tau$ & $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ are 3-body decays into 3 spin 1/2 particles, only 1 observed
  $\to$ signal strongly diluted

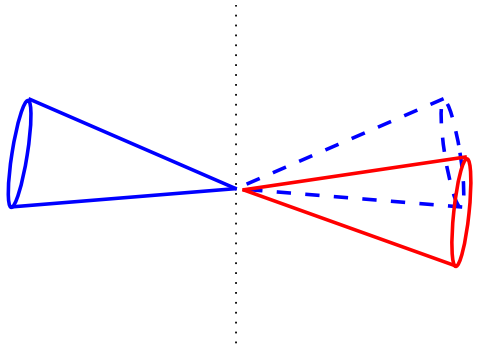
- Decays modes to spin-1 mesons (ρ, a_1) more complicated, two spin configurations of the meson. But subsequent decays ($\rho \to 2\pi$, $a_1 \to 3\pi$) give info on meson spin state.
  $\to$ part of τ polarization regained

	$\tau \to e\nu\nu$ $\tau \to \mu\nu\nu$	$\tau \to \pi\nu$ $\tau \to K\nu$	$\tau \to \rho\nu$	$\tau \to a_1\nu$
Br	0.35	0.12	0.25	0.09
Sens.	0.22	0.58	0.49	0.45
Weight	0.12	0.30	0.44	0.13

Polarization determined by fitting MC spectra for $\langle P_\tau \rangle = 1$ and $\langle P_\tau \rangle = -1$ to data.

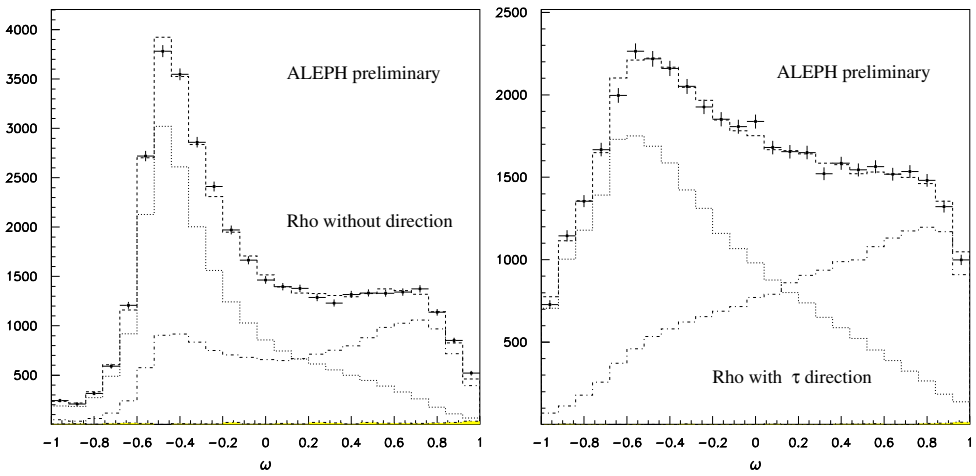


Recent progress by new ALEPH analysis:
$\tau^+\tau^-$ direction determined for whole event:



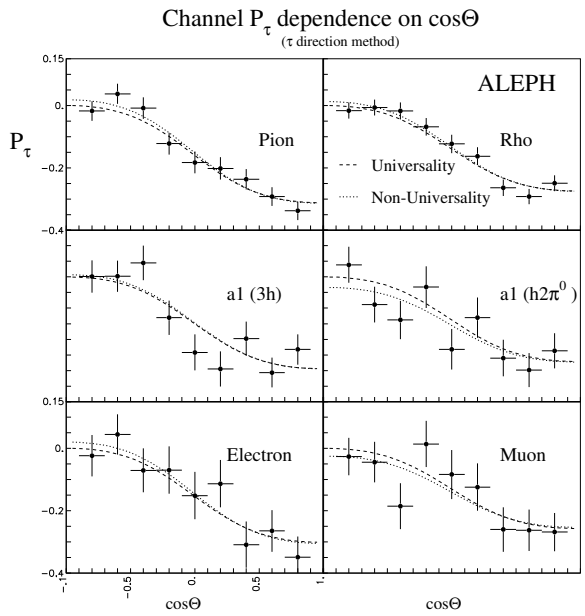
τ direction given by intersection of cones (2 fold ambig.)

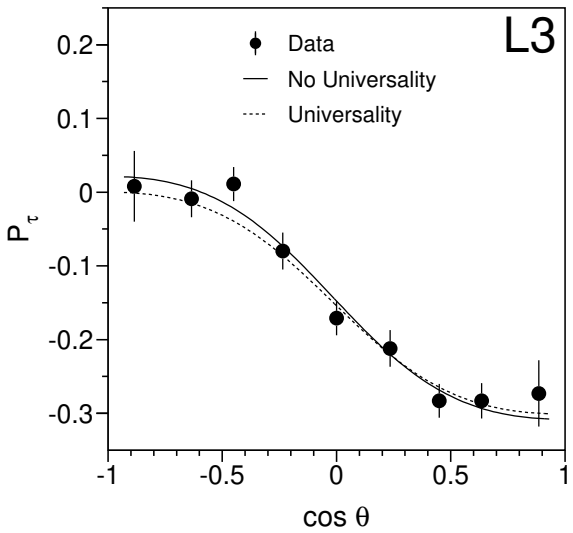
Improves sensitivity of a_1 and ρ channels
(0.48→0.58)



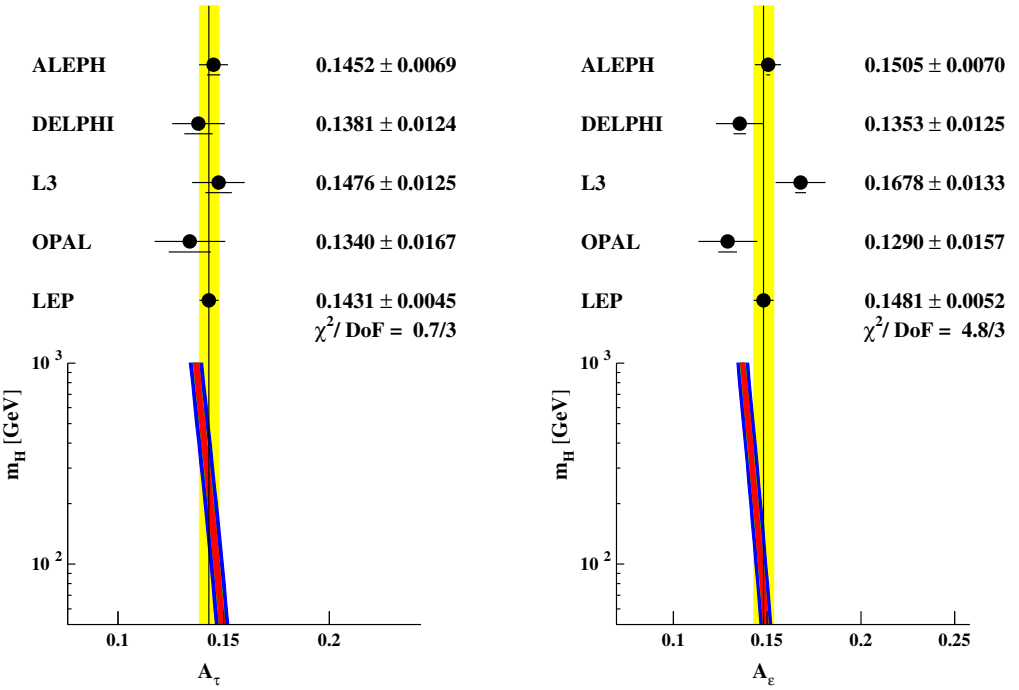
Angular distribution

$\langle P_\tau \rangle$ and $A_{\rm FB}^{\rm pol}$ determined by fitting observed $d\langle P_\tau \rangle / d\cos\theta$





Combined Results

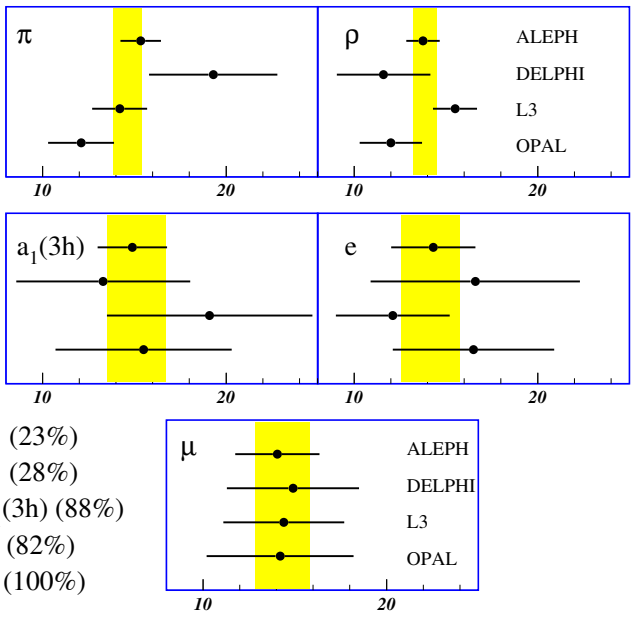


Systematics mostly uncorrelated among experiments: Detector simulation, PID and calibration.

Correlated sources (a_1 decay, τ Br's, corrections) at the 1-2 % level.

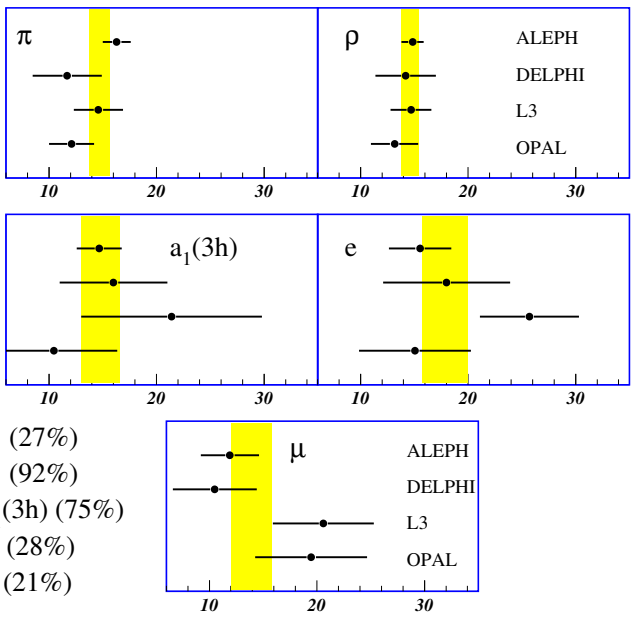
Results by Channel

A_τ measurements by channel at LEP



π (23%)
ρ (28%)
a_1(3h) (88%)
e (82%)
μ (100%)

A_e measurements by channel at LEP



π (27%)
ρ (92%)
a_1(3h) (75%)
e (28%)
μ (21%)

Detector characteristics

Significant differences in precision already reflected in $\tau^- \to \nu_\tau \rho^-$ efficiency & purity.

	ALEPH	DELPHI	L3	OPAL
eff.	51 %	41 %	58 %	41 %
bkgr.	8.9 %	15 %	10.5 %	27 %

τ polarization poses specific challenges on ECAL performance. Most crucial π^0 id and separation of $\pi^0, \pi^\pm$ showers.

	ALEPH	DELPHI	L3	OPAL
Magnet	1.5 T	1.23 T	0.5 T	0.435 T
ECAL				
granularity	$3 \times 3 cm^2$	$2 \times 2 cm^2$	$2 \times 2 cm^2$	$10 \times 10 cm^2$
energy σ_E/E	$0.18/\sqrt{E}$	$0.32/\sqrt{E}$	$0.02/\sqrt{E}$	$0.06/\sqrt{E}$

Interpretation

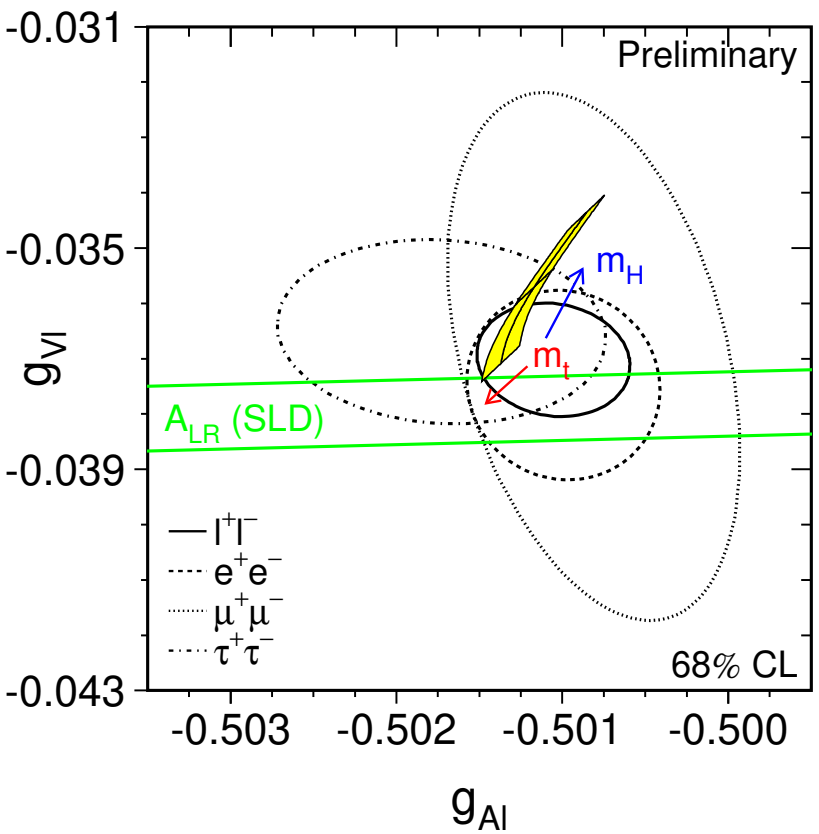
Lepton universality:

Couplings $\hat{g}_v^l$ & $\hat{g}_a^l$ given by:

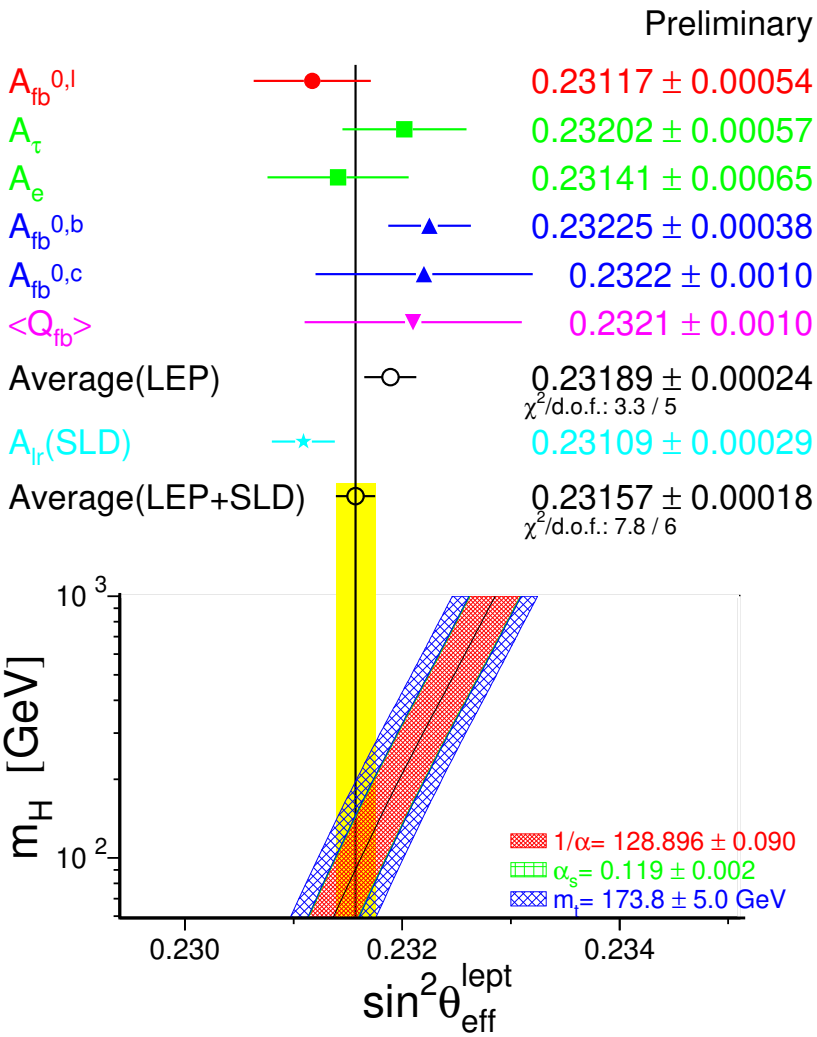
$\Gamma_l \propto (\hat{g}_v^l)^2 + (\hat{g}_a^l)^2$

$A_{\rm FB}^{0,l} \propto (\hat{g}_v^l/\hat{g}_a^l)^2$

$\langle P_\tau \rangle$ and $A_{\rm FB}^{\rm pol} \propto (\hat{g}_v^l/\hat{g}_a^l)$



$\sin^2\theta^{l}_{\mathrm{eff}}$



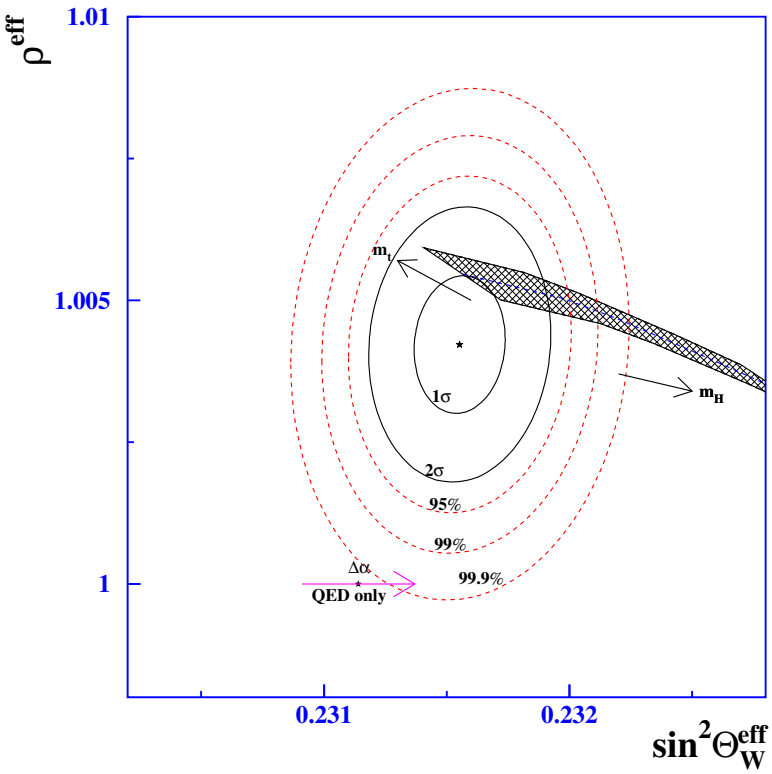
χ^2 quite ok now, was $12/6$ at EPS 1997

$(P(\chi^2) : 5\,\% \rightarrow 25\,\%)$

A_{LR} and $A_{\mathrm{FB}}^{0,b}$ disagree by about $2.5\ \sigma$.

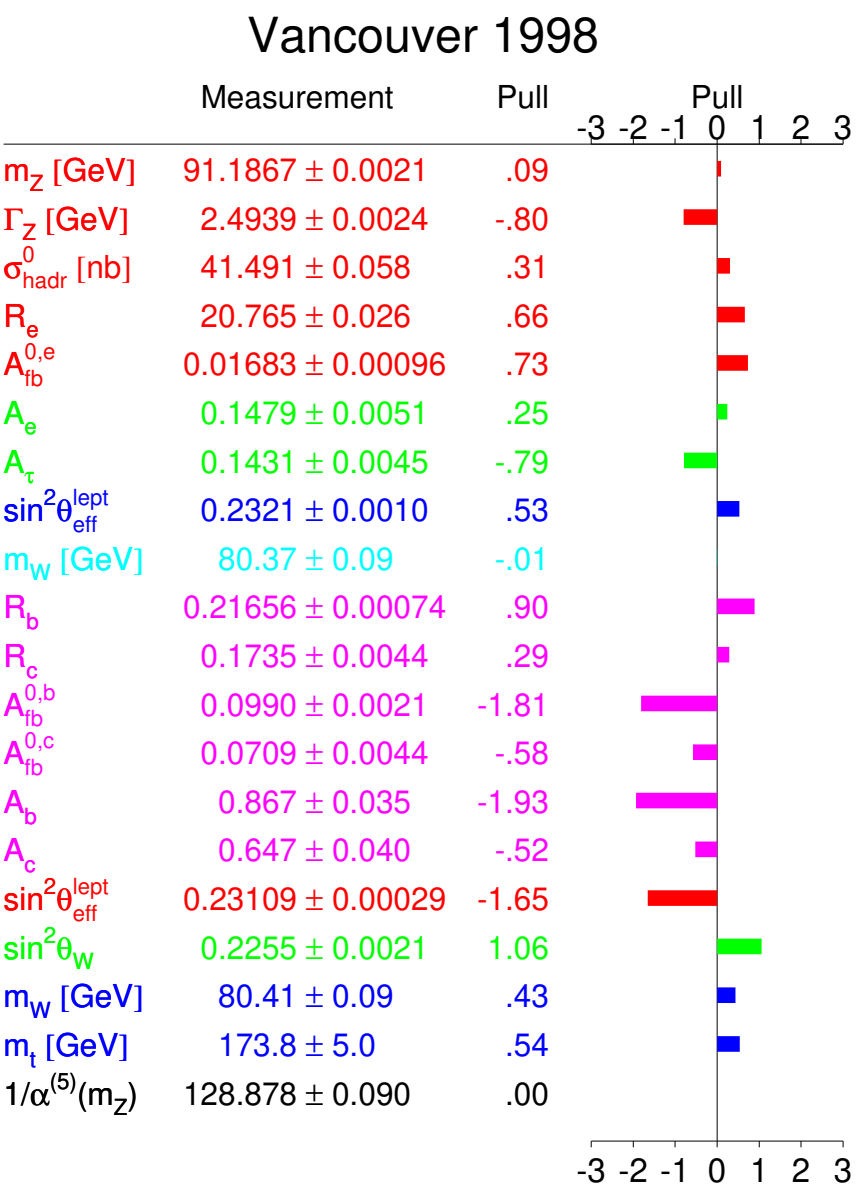
$\rho^{\ell}_{\mathrm{eff}}$ vs $\sin^2\theta^{\,l}_{\mathrm{eff}}$

$$\Gamma_l \propto \rho = \frac{1}{1-\Delta\rho}$$



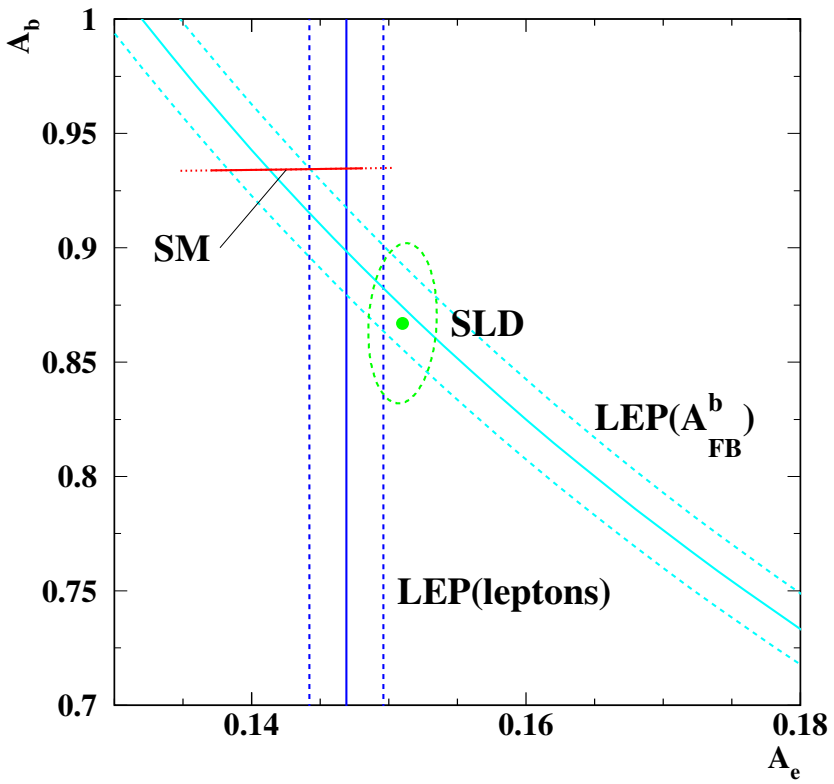
Presence of genuine electroweak corrections with >99 % C.L. (mainly due to ρ)

Pulls for SM fit



Overall χ^2/d.o.f. ok with $15/15$, no measurement more than $2\ \sigma$ away.
but $A^{0,b}_{\rm FB}$, A_{LR} & and $\mathcal{A}_b$ alone give $\chi^2 = 9.7$.

LEP and SLD asymmetries



Summary

- Lepton charge asymmetries essentially finalized. No change expected.
- Heavy quark asymmetries full statistics analyzed. Small improvements in some areas with refined analyses possible.
- Precision of LEP tau polarization substantially improved last year. Most analyses use full statistics. Some further gain in accuracy likely.
- Discrepancy in $\sin^2\theta^l_{\rm eff}$ measurements significantly reduced ($P(\chi^2) = 25\,\%$).

Standard Model still in perfect shape !